PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN H $\rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2022

This work is dedicated to the living and loving memory of Jacob Myhre.

ACKNOWLEDGEMENTS

Without so many two- and four-legged blessings along the way, I could never have made it to this point in my academic career. Thus, I begin by giving my endless gratitude to my high energy physics mentors, Professors Andrey Korytov and Guenkah Mitselmakher, for granting me this one-of-a-kind opportunity to do real *science* at CERN.

To my wife, Suzanne Rosenzweig, for showing me that dreams *do* come true. To my mother and father, Vicki and John, who always reassured me that I could achieve anything I put my mind to. Sleep peacefully, Mom. To my siblings, Alex, Ryan, Devin, Jace, and Claudia who frequently and gently reminded me that life existed outside of grad school. To Auntie Rachel and Uncle Yuri, who just *get* me and have given to me everything I could have possible asked for. To my mentor, Sheldon Friedman, and his wife, Rita Friedman (Rosenzweig), who chose to invest in my success at a young age. I have only made it this far thanks to their undying encouragement, love, and optimism. To Sheldon's best friend, Dr. Bernard Khoury, whose reputation and has helped pave my own path. To the many moms who generously gave unconditional support during the darkest of times and unequivocal love during the brightest times: Cyndi Reilly-Rogers, Dawn Hood, Margaret Sherrill, and Silet Wiley.

To Dr. Filippo Errico for his focus, leadership, selflessness, and patience in leading the Higgs mass analysis. To Dr. Lucien Lo for showing me the simplicity and beauty of Python in his typical laid-back way and for leading the dilepton analysis. To Dr. Noah Steinberg for showing me how majestically physics can be communicated from mind to mind. To Dr. Darin Acosta, for spending many hours of physics discussion with me and the other students, who have helped us build our "CMS Office Hours" Ari Gonzalez, Cris Caballeros, Jeremiah Anglin, Sean Kent, Evan Koenig, Neha Rawal, Nik Menendez, John Rötter. To the gents who paved my way to and through the world of CMS, Brendan Regnery and Bhargav Joshi. To my mentee, Matthew Dittrich, for accepting the baton of knowledge and making everything come full circle.

To my comrades for showing me what it takes to survive the core courses, Dr. Atool Divakarla, Dr. Brien O'Brendan, Dr. Donyell Guerrero, and Dr. Vladinar Martinez. To Adamya Goyal for all his gentleness, humility, patience, and tutorage. To my Polish roommates in Saint-Genis-Pouilly for showing me what home away from home feels like: Bartoszek, Dziadziuś,

Karolina, and Sandruśa. To the boys who have been there since the beginning: Jish, Willis, The Shane, Zacman, Duck, and Marcus for their clever competition and continual camaraderie which has shaped me to this day.

To Big Tree who stood as a symbol of strength, beauty, and life for centuries before us. As Irma's wild whirring winds worsened, the cacophony of ripping roots resounded throughout the western corridor. There I stood in that frozen moment—awestruck, speechless—watching her *fall* helplessly towards the physics building. What could have been a catastrophe of cataclysmic proportions was instead a gentle grazing against the north windows of NPB where, there, she was gracefully laid to rest.

Finally, to Existence, for this unpredictable, unbelievable blip of an experience called Life.

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PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN $\mathrm{H} \rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

Jake Rosenzweig

December 2022

Chair: Andrey Korytov
Co-Chair: Guenakh Mitselmakher
Major: Physics

The mass of the Higgs boson is measured in the $\mathrm{H} \rightarrow \mathrm{ZZ}^* \rightarrow 4\ell$ ($\ell = \mathrm{e}, \mu$) decay channel and is found to be $m_{\mathrm{H}} = 125.38 \pm 0.11\,\mathrm{GeV}$; the most precise measurement of m_{H} in the world to date. The data for the measurement were produced from proton-proton (pp) collisions at the Large Hadron Collider with a center-of-mass energy of 13 TeV during Run 2 (2016–2018), corresponding to an integrated luminosity of $137.1\,\mathrm{fb}^{-1}$, and were collected by the Compact Muon Solenoid experiment. This measurement uses an improved analysis technique in which the final state muon tracks are constrained to originate from the primary pp vertex. Using data sets from the same run, a search for low-mass dilepton resonances in Higgs boson decays to the 4ℓ final state is also conducted. No significant deviation from the Standard Model prediction is observed.

CHAPTER 1
INTRODUCTION

The Universe, while overwhelmingly vast, is built from a remarkably few kinds of elementary (i.e., indivisible) particles. As shown in Fig. 1-1, any elementary particle can be classified into 1 of these 3 categories: matter particles (*fermions*), force-carrying particles (*gauge bosons*), and Higgs bosons. There are 12 kinds of fermions which can be split evenly into 2 groups, depending on with which forces they interact: those that interact via the electromagnetic (EM) force and the weak nuclear force are classified as *leptons*, of which there are 6 kinds (*"flavors"*), whereas those that interact via the EM, weak, *and* strong nuclear forces are classified as *quarks*, of which there are also 6 flavors. There are 4 kinds of gauge bosons, each of which is a force carrier for a specific force (the gluon is said to *mediate* the strong force, the photon mediates the EM force, while both the $W^{\pm}$ and Z bosons mediate the weak force). Thus, all the diversity and manifestations of reality come from only 17 kinds of "building blocks". It is the mission of particle physicists to understand the underlying mathematical structure that describes Nature in as accurate—and concise—a theory as possible. The best theory that stands today is called the Standard Model (SM) of particle physics.

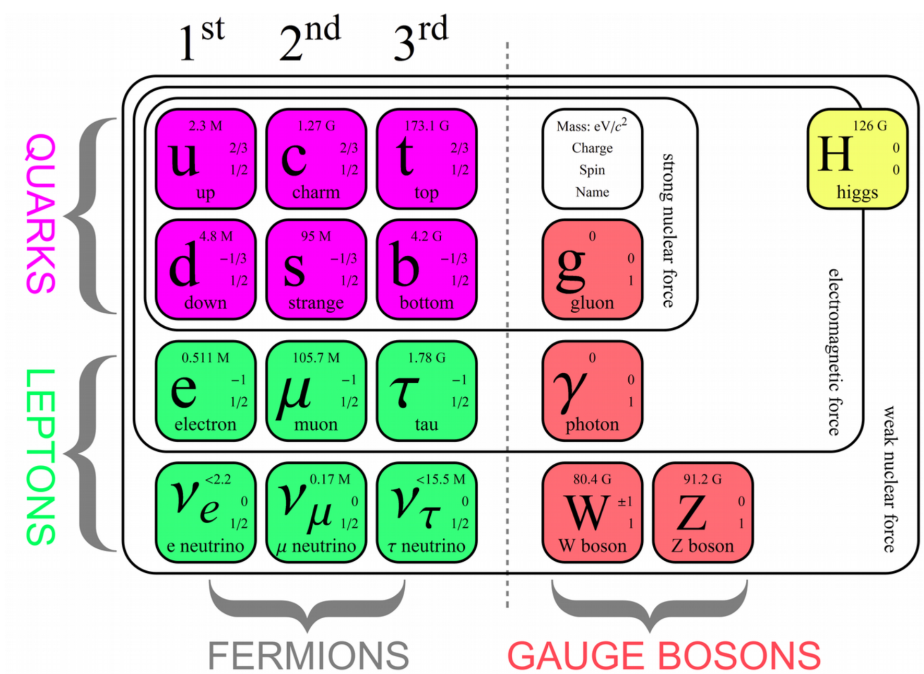

Figure 1-1. The elementary particles described by the SM.

The SM has bore witness to many triumphs over its approximately 70-year development: it predicted the existence of quarks which were experimentally confirmed in the mid-1970s; it predicted the existence of the tau neutrino which was experimentally confirmed in 2000; its most groundbreaking prediction was experimentally confirmed on July 4, 2012—just shy of 10.5 years ago from the date of this dissertation writing—when the ATLAS and CMS collaborations announced the discovery of the Higgs boson [1–3].

Quantum Field Theory is the mathematical and conceptual backbone of the SM. Within its framework, all particles are *excitations* of their corresponding field so, e.g., *every* electron in the Universe is thought to be an excitation of the single electron field that permeates all of spacetime. The existence of the Higgs boson (H) suggests that its corresponding field exists—the *Higgs field*—and, thus, H is the quantum excitation of that field. This all-pervasive Higgs field and its corresponding boson are generated mathematically via the Brout-Englert-Higgs (BEH) mechanism. Most SM particles—except for neutrinos, photons, and gluons—"acquire" their mass by interacting with the Higgs field. This is also how the Higgs boson itself acquires its mass (m_{H}); by interacting with its own field!

The masses of SM particles *depend* on the value of m_{H} . . . *so what is its value?* Unfortunately, m_{H} is a free parameter of the SM, so theory is unable to provide a value for m_{H} based solely on other fundamental constants. Instead, the value of m_{H} must be measured by experiment—and has been measured multiple times [4–6]. Although m_{H} has already been measured, it is important to continually improve the measurement by lowering the uncertainties on (i.e., increasing the precision on) the mass value. A more precise value of m_{H} is two-fold: first, it improves the theoretical limits on the masses of the other elementary particles and, second, it very well may determine the stability of our universe, as shown in Fig. 1-2.

The production of a Higgs boson is only feasible at conditions close to those thought to exist at the beginning of the Universe. This grand achievement is accomplished frequently by the Large Hadron Collider (LHC), located on the border of France and Switzerland. It is the largest and most powerful proton-proton (pp) collider ever made. The LHC accelerates protons to incredible

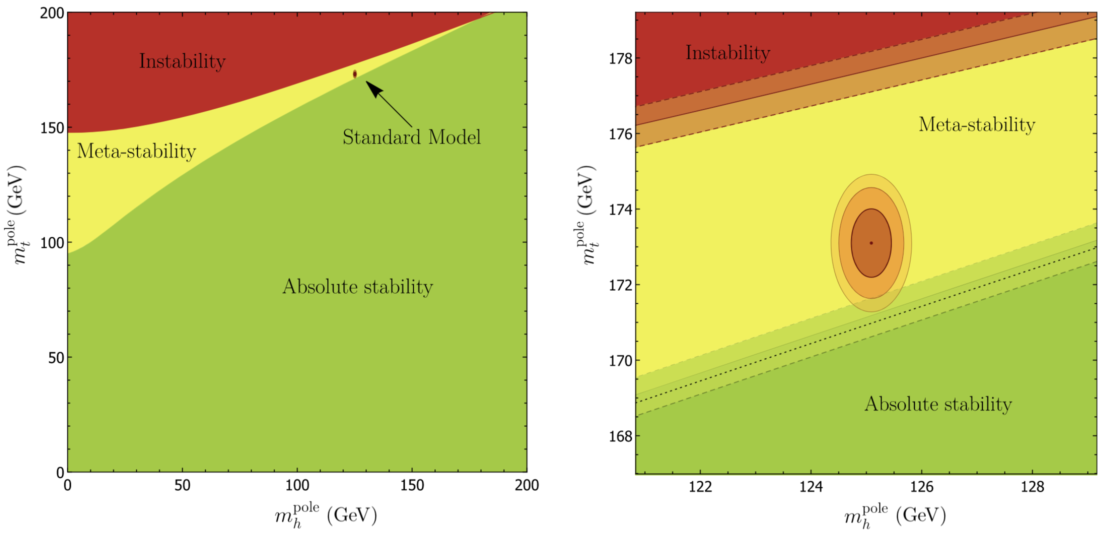

Figure 1-2. (Left) Theoretical stability regions of the Universe based on the pole masses of the top quark $\left(m_t^{\text{pole}}\right)$ and Higgs boson $\left(m_h^{\text{pole}}\right)$. (Right) A closeup of the SM region of the left plot. The contours represent the 68%, 95%, and 99% confidence levels based on the experimental uncertainties of m_t^{pole} and m_h^{pole}. Plots taken from [7] and units added to all axes.

speeds, very close to the speed of light. When these fast-moving protons collide, the pp collisions can have a center-of-mass energy as high as 13 TeV. Newly produced particles spew out of the collision points and are analyzed by detectors like the aforementioned ATLAS and CMS experiments. These enormous particle detectors have thousands of scientists performing dozens of analyses to look for hints of beyond Standard Model (BSM) physics, extra dimensions, miniature black holes, and more.

This dissertation utilizes data collected by the CMS experiment during the LHC Run 2 (2016–2018) to perform the world's best precision measurement of m_{H} to date. This new measurement utilizes the following improvements compared to previous measurements:

- Nearly four times as much collected data from Run 2 $\left(L_{\text{int}} = 137.1\,\text{fb}^{-1}\right)$ vs. the data used for the 2016 measurement $\left(L_{\text{int}} = 35.9\,\text{fb}^{-1}\right)$.
- Four final-state categories: 4μ, 4e, 2e2μ, 2μ2e. In previous measurements, the last two final states (the mixed-flavor states) were combined, when truly they have different kinematical properties (depending on into which lepton pair the Z_1 decayed): different peak widths (instrumental resolutions), different signal efficiencies, and different relative levels of

reducible background.

- Ultra-Legacy (UL) reconstruction for muon, electron, photon, and jet tracks. This signficantly improves electron momenta and improves the other particle momenta, though to a lesser degree.
- The measurements of muon p_{T} are improved by constraining the muon tracks to originate from the interaction vertex (also called a *vertex constraint*).
- When extracting the value of m_{H} in past measurements, a 3D pdf $\left(m_{4\ell}, \sigma_{m_{4\ell}}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}\right)$ was built into a factorized form $f\left(m_{4\ell}, \sigma_{m_{4\ell}} \middle| m_{\mathrm{H}}\right) \cdot g\left(\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} \middle| m_{4\ell}\right)$, which was later found to contain an existing correlation between $\sigma_{m_{4\ell}}$ and $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$. To account for this correlation, now the events are split into 9 categories based on the per-event *relative* mass uncertainty $\left(\frac{\sigma_{m_{4\ell}}}{m_{4\ell}}\right)$ and, for each, a 2D pdf $\left(m_{4\ell}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} \middle| m_{\mathrm{H}}\right)$ is built.
- The systematic uncertainties on electron and muon momentum scales $\left(p_{\mathrm{T}}^{\mathrm{e},\mu}\right)$ are reduced, thanks to a more detailed analysis on the uncertainties. This has the additional effect of significantly reducing the uncertainty on the per-event four-lepton mass resolution.

The following chapters of this dissertation begin by describing the function and engineering of the Large Hadron Collider in Chapter **??**. Then, a thorough description of the CMS Experiment and its composite subdetectors is given in Chapter **??**. Next, the details of the precision measurement of the Higgs boson mass using the LHC Run 2 data is discussed in Chapter **??**. Finally, the results of the Higgs boson mass measurement analysis is summarized in Chapter **??**.

CHAPTER 2
ALPHABET SOUP: H, SM, BEH, EWSB

The Standard Model (SM) is a collection of the most accurate and self-consistent particle physics theories that mathematically describe the properties of particles within the universe and their interactions with each other. For the past century, some of the most brilliant minds in physics have spent their entire careers to develop equations, mathematical tricks, and completely novel ideas to help build a solid foundation for the SM. To demonstrate the unparalleled accuracy with which the SM predicts physical phenomena, one can compare the experimentally measured anomalous magnetic moment of the electron

$$a_e^{\text{exp}} = 0.001\,159\,652\,180\,73(28)$$

to the value predicted by the SM

$$a_e^{\text{pred}} = 0.001\,159\,652\,181\,643(764).$$

An impressive agreement to better than one part per trillion.

On the other hand, the SM has no explanation for some observed physical phenomena (Sec. 2.4), e.g., the existence of dark matter [8], and is thus not a fully descriptive model of the Universe. Furthermore, the Collider Detector at Fermilab (CDF) Collaboration recently measured the mass of the W boson to be $80\,433.5 \pm 9.4\,\text{MeV}$, whereas the SM expectation $80\,357 \pm 4\,\text{MeV}$—a discrepancy of 7.0 standard deviations [9]—as is shown in Fig. 2-1. Recent results from the Baksan Experiment on Sterile Transitions suggest electron neutrinos oscillating between sterile neutrino states [10]. Nevertheless, the SM has laid important foundations in particle physics for over 100 years and is fully explained with the discovery of the Higgs boson in 2012 TODO:CITE.

The remainder of this chapter presents a general overview (Sec. 2.1) of the particles and forces described by the SM, followed by a brief analysis of the mathematical underpinnings of the SM (Sec. **??**), and then finally a brief description of the shortcomings of the SM (Sec. 2.4).

SM OF PARTICLE PHYSICS CHAPTER OUTLINE OVERVIEW: - Main concept: - Everything is particles! Fields permeate all of space. Their mathematical treatment is handled in Sec.TODO. Particles are excitations of the fields. Interactions are between particles Bosons

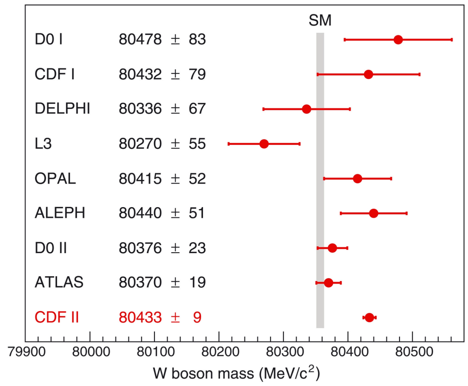

Figure 2-1. Precision measurements of the W-boson mass performed by various collaborations.

Fermions Leptons Quarks MATHEMATICAL FRAMEWORK - Show SM Lagrangian. - Derive interactions between particles. BEH MECHANISM - Robert Brout, François Englert, and Peter Higgs claimed that elementary particles acquire their masses via spontaneous EWSB. (reword!) - Sheldon Glashow, Abdus Salam, and Steven Weinberg were able to unify the weak and electromagnetic forces into a single force, above the unification energy of 246 GeV. - In 1973 the Gargamelle collaboration experimentally confirmed the existence of the electroweak force by discovering neutral currents in neutrino scattering experiments. - Furthermore, in 1983 the UA1 and UA2 collaborations used proton-antiproton collisions to discover the theorized W and Z electroweak gauge bosons. SHORTCOMINGS OF THE SM - Each of these is a new paragraph?: - Neutrino oscillations confirm that neutrinos *do* have masses but interaction with the Higgs field is not responsible for this origination. - No gravity. - Why matter and no antimatter? - Where does dark matter fit in? - Why should there be exactly 3 generations of fermions? - Although the SM does not answer any of the above questions,

2.1 Overview

The SM is a renormalizable quantum field theory defined in terms of a Lagrangian tha describes interactions between fundamental particles as governed by the strong, weak, and electromagnetic forces. It is a non-Abelian gauge theory comprising interacting field theories based on gauge invariance constructed within the framework of quantum mechanics and special relativity. The SM exhibits invariance under the symmetry group

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \tag{2-1}$$

where $\mathrm{SU}(3)_C$ invariance explains the existence of gluons (g) as the mediators of the strong force, described by quantum electrodynamics (QCD), and the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ invariance results in the $W^{\pm}$, Z^0, and γ bosons as mediators of the electroweak force, described by the unified electroweak theory and quantum electrodynamics. Interactions via the strong, electromagnetic, and weak forces are restricted to particles carrying a color charge, electric charge, and a weak charge, respectively. The SM formulation lacks the ability to describe gravity on a quantum level and might actually be incompatible with the most successful modern theories of gravitation. Gravitational effects are negligible at subnuclear scales.

The Particles: The Players on the Fields

Contrary to intuition, fundamental particles are not hard, billiard-ball-like objects as is often perceived. Instead the SM predicts that every particle is actually an *excitation* of its corresponding field. So for example the electron is an excitation of the *electron field*, $\psi_e(x)$, a bispinor that describes a spin-1/2 field which follows the Dirac equation: In fact, *every* electron is an excitation of this same electron field. An electron is identical to every other electron in every way (same mass, same charge, etc.). Quantum Mechanics (QM) does a fine job of describing how slow-moving particles behave. However, as soon as particles begin moving at 30.5% of the speed of light (91.4 $91.4E6$ m/s), then there is a 5% difference between the particle's rest mass energy ($E = mc^2$) and its total relativistic energy ($E = \gamma mc^2$). In other words, fast-moving particles must account for effects due to Special Relativity (SR). The merger of QM and SR gives rise to Quantum Field Theory (QFT) - the backbone of the SM.

Fig. 2-2 shows all the fundamental particles that have been discovered up to the present day. The phrase "fundamental particle" just means that the particle is not composed of anything smaller than itself. These particles are not just diabolical creations from theorists. No, these particles are precisely defined, mathematical objects whose existence has been predicted by the SM and experimentally verified time and time again in the laboratory.

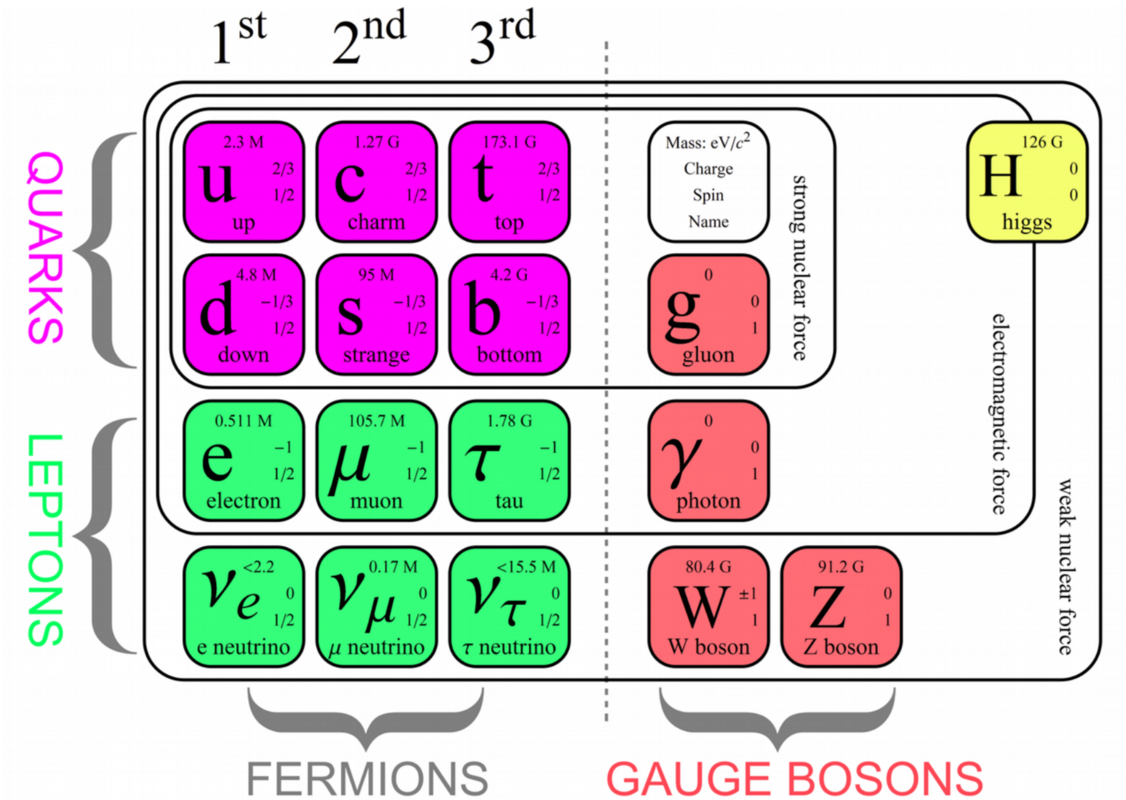

Figure 2-2. The fundamental particles of the Standard Model.

Each particle has a unique set of properties (like mass, electric charge, spin, etc..) that distinguish it from all the other particles. It is one of the primary goals of particle physics to determine these properties, because ultimately their properties determine their *interactions* with one another.

Without further ado, let's meet the particles. There are two major types: *bosons* and *fermions*. We are going to take a non-traditional route and introduce the bosons first, then the fermions.

Bosons: Use the Force

Ever wonder how two electrons "know" that they are near each other and that they should repel? Fig. 2-3 shows a Feynman diagram of two electrons "communicating" with each other by means of an intermediate photon. I like to think of it as the two electrons "playing catch" with the photon. The first electron recoils from the throw and then the second electron recoils from catching the photon. The photon carries some momentum away from the first electron and brings it to the second one, therefore making it look as if the two electrons are repelling one another! The photon isn't *real* of course - it is said to be a *virtual* photon. Now we see why bosons are called the force carriers.

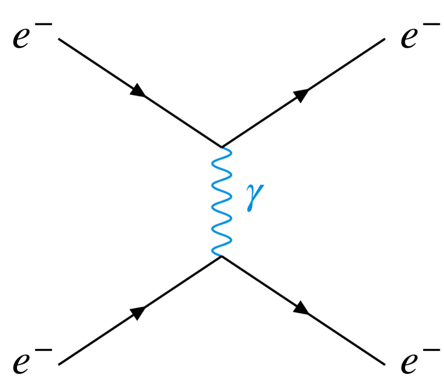

Figure 2-3. A Feynman diagram showing electron-electron scattering, also known as Møller scattering.

A diagram such as the one above is a Feynman diagram and it gives us a wonderfully simple way to visualize particle physics processes. It's not *actually* what happens between the particles, but it is a good starting point. Each diagram is actually a single, scalar number - a complicated

QFT integral that tells you how likely a process is to happen. Another benefit to Feynman Diagrams is that they are kind of like tinker toys, in that you can string them together in novel ways to predict real-world processes. Quantum Electrodynamics (QED), one of the theories that make up the SM, mathematically describes and predicts the electrons mediating such a photon between them. It's not just limited to electrons mediating photons, however. QED and other QFTs can predict to astounding accuracy how likely a process is to happen, between whichever particles and fields. You just need to know their properties first.

We have now met the first force carrier: the photon. It is a massless particle and is the mediator of the EM force. Photons only interact with particles that carry *electric charge*. Depending on what kind of charge a particle carries, determines with which bosons it may interact and via which forces. Speaking of forces, the four fundamental forces found in nature, along with their decreasing, relative strength are:

1. strong force (1)
2. EM force (10^{-1})
3. weak force (10^{-6})
4. gravitational force (10^{-40})

If the photon is the mediator of the EM force, then what mediates the other forces?

The mediators of the strong force are the 8 **gluons**. Similar to the photon, they are also massless, but that's about all they have in common. Gluons are trapped inside of protons, neutrons, and other hadronic matter. They are responsible for "glueing" nuclei to together, hence their name. Just as photons can only interact with particles that have electric charge, gluons can only interact with particles that have *color* charge. Interestingly, gluons themselves carry color charge which they mediate back and forth between quarks (fermions discussed below). This is quite different from the photon which itself does not carry electric charge. There are three kinds of color charges: red, green, and blue. Every gluon carries two color charges: one kind of color and an anticolor: antired, antigreen, or antiblue.

There are three bosons which mediate the weak force: the Z, W^+, and W^-. They are extraordinarily massive particles, weighing in at 91.2 GeV for the Z and 80.4 GeV for both kinds of W bosons. That means the W bosons weigh more than an iron atom! These bosons interact with any particle that carries "weak hypercharge". The weak force has plagued physicists for nearly a century until only recently. Particles which decay via the weak force live an astonishingly long time. Take for example the neutral pion (π^0). It decays very quickly, via the EM force, into two photons on the order of 10^{-18} s. Now take the charged Kaon K^+. This particle decays into three charged pions, but takes on average 10^{-8} s to do so. Over 10 orders of magnitude different from the pion decay. This is because the charged kaon decays via the weak force.

The last boson not yet mentioned is the scalar Higgs boson, which is introduced in Sec.TODO below.

Fermions: Each One Matters There are 12 kinds of fermions - the matter particles of the Universe. They comprise all the "stuff" that we see and feel. All fermions have half-integer spin, typically a value of 1/2. The fermions can be split into two groups depending on if they interact with the strong force (quarks) or not (leptons). Let's consider the leptons first.

Leptons: We already introduced one lepton earlier: the electron. Looking again at the "particular table", the electron has a heavier brother, the muon, which is 200 times heavier than the electron. Then there is an even heavier sibling: the tauon. All three of these leptons have the familiar -1 charge which allows them to interact via the EM force and exchange photons with other electrically charged particles.

The charged leptons also carry weak hypercharge, which allows them to interact via the weak force. If a charged lepton interacts with a $W^\pm$ boson, it can transform into its corresponding "partner" - the other member of the $SU(2)$ isospin doublet: the neutrino. These fickle particles are neutral and *only* interact via the weak force (well, and maybe gravity). They are very difficult to detect.

Quarks: The six quarks are the fermions which interact with gluons. They have *quarky* names like: up, down, charm, strange, top, bottom. These are called the six "flavors" of quarks.

The top quark is an absolutely massive particle, reaching the top of the mass scale of any particle at 173 GeV - about as heavy as a tungsten atom.

Quarks are electrically charged particles, but they have fractional charge. Each quark in the top row of Fig. 2-2 has +2/3 electric charge and the bottom row has -1/3. That's why when you combine two up quarks with a down to form a proton quark, the combination of electric charge yields +1.

Just as the leptons carried weak hypercharge and could interact via the weak force, so too can quarks. The $W^{\pm}$ bosons can change one flavor of quark into another. The Z boson only affects the spin, momentum, and energy of the particle with which it interacts.

In addition to electric charge, quarks also carry one kind of color charge, either red, green, or blue. It is this color charge which allows them to interact with gluons via the strong force. This is an artifact of being gauge bosons of the $SU(3)$ symmetry group. They combine in different ways to form at least two types of hadrons. The first type is baryons, like protons, neutrons, lambdas (anything that is qqq) and the second type is mesons, like pions, kaons, etas (anything of some form like $q\bar{q}$). For some reason which is not completely understood, only colorless bound states form in nature. Just as a '+' charge would negate a '$-$' charge, so too would the 'red' color charge negate 'antired' (as in the case of an observable meson) or even combining red, green, and blue (as in the case of a baryon) would yield a colorless bound state.

Antiparticles: It should be noted that almost every *particle* has a corresponding *antiparticle*, whose charges (e.g.,, color charge, electric charge) are all opposite the original particle's charges. Accounting for leptons, quarks, bosons, bound states of quarks, and now antiparticles, it is easy to see why sometimes particle physics is referred to as a "zoo"!

2.2 Electroweak Symmetry Breaking

The main objective of the LHC is to probe the Electroweak Symmetry Breaking (EWSB) mechanism that generates the masses of the known elementary particles in the SM. The discovery of the Higgs boson in 2012 by the ATLAS [11] and the CMS [12] collaborations and the subsequent studies of its properties with the full data set from Run 1, from 2009 to 2012, with a center-of-mass energy of 7 TeV and 8 TeV, provided the first opportunity to study this mechanism. The data collected during the LHC Run 2, from 2015 to 2018, with a higher center-of-mass energy of 13 TeV and more robust dataset, revealed the compatibility of the Higgs boson and its role within the Standard Model (SM) [13–15].

In the SM, the electroweak interactions are described by a gauge field theory invariant under the $SU(2)_L \times U(1)_Y$ symmetry group. The mechanism of EWSB [16, 17] provides a general framework to preserve the structure of these gauge interactions at high energies along with the generation of the observed masses of the W and Z gauge bosons. The EWSB mechanism posits a self-interacting complex EW doublet scalar field, whose CP-even neutral component acquires a vacuum expectation value (vev) $v \equiv 246$ GeV, which sets the scale of the symmetry breaking. Three massless Goldstone bosons are generated and are absorbed to give masses to the W and Z gauge bosons. The remaining component of the complex doublet becomes the Higgs boson, a new (and thusfar unique) fundamental scalar particle. The masses of all fermions are also a consequence of EWSB since the Higgs doublet is postulated to couple to the fermions through Yukawa interactions.

The initial measurements during the LHC Run 1 were accessible mainly through production and decay channels related to the couplings of the Higgs boson to the vector gauge bosons (the mediators of the electroweak interactions, $W^{\pm}$, Z and γ, as well as the gluons, g, mediators of the strong interactions). The outstanding performance of the LHC Run 2, made it possible for the ATLAS and CMS experiments to independently and unambiguously establish the couplings of the Higgs boson to the charged fermions of the third generation (the top quark, the bottom quark, and the tau).

In all observed production and decay modes measured so far, the rates and differential measurements are found to be consistent, within experimental and theoretical uncertainties, with the SM predictions. In high resolution decay channels, such as the ones with four leptons (electrons or muons) or diphoton final states, the mass of the Higgs boson has been measured at the permill precision level.

Nevertheless, several channels are still out of reach experimentally and the couplings of the Higgs boson to light fermions are yet to be explored. Moreover, within the current precision, a more complex sector with additional states is not ruled out, nor has it been established whether the Higgs boson is an elementary particle or whether it has an internal structure like any other scalar particles observed before it.

Without the Higgs boson, the SM would not have been calculable. In particular, perturbative unitarity [18–21] would be lost at high energies since the longitudinal W/Z boson scattering amplitude would grow with the center-of-mass energy. In addition, the radiative corrections to the gauge boson self-energies would exhibit dangerous logarithmic divergences that would be difficult to reconcile with EW precision data. The discovery of the Higgs boson verified that the SM is a spontaneously broken gauge theory and, as such, it could a priori be consistently extrapolated well above the masses of the W and Z bosons. Formally there is no need for new physics at the EW scale, though as the SM Higgs boson is a scalar particle, at the quantum level it has sensitivity to possible new physics scales. Quite generally, the Higgs boson mass is affected by the presence of heavy particles and receives quantum corrections which destabilize the weak scale barring a large fine tuning of unrelated parameters. This is known as the Higgs naturalness or hierarchy problem [22, 23]. It has been the prime motivation for new physics searches at the TeV scale. New theoretical paradigms have been imagined, such as a new fermion-boson symmetry called supersymmetry (SUSY) [24] (for recent reviews, see Refs. [25, 26]), or the existence of strong interactions at a scale of the order of a TeV from which the Higgs boson would emerge as a composite state [27] (see Refs. [28–30] for recent reviews). Alternatively, new agents stabilizing the weak scale could also be light yet elusive, such as in models of neutral naturalness [31–34]. Other more recent scenarios [34–36], instead, rely on the cosmological evolution of the Universe to drive the Higgs boson mass to a value much smaller than the cutoff of the theory and aim at alleviating the hierarchy problem without the need for TeV scale new physics, though there might still be interesting and spectacular signatures [34–37]. Beyond the naturalness problem, extensions of the SM Higgs sector without other low-energy particles have been proposed, for example, to provide explanations for the fermion mass hierarchies, see e.g. Ref. [38, 39], to account for the Dark Matter abundance, see e.g. Ref. [40], or to modify the properties of the electroweak phase transition [41]. Such models with additional scalars provide grounds to explore new Higgs boson signals in concrete and complete scenarios, with different types of coupling structure to fermions and gauge bosons.

The Higgs boson is special and, in the eight years since its discovery, it has become a powerful tool, providing the capability to explore the manifestations of the SM and to probe the physics landscape beyond. It may offer direct insight on physics beyond the weak scale through possible sizeable effects on the Higgs boson properties. However, the Higgs boson couplings have thusfar been observed to be in good agreement with their SM predictions. This, together with the strong bounds from precision electroweak and flavor data, provides the possibility that the Higgs boson may well be elementary, weakly coupled, and solitary up to the Planck scale, rendering the EW vacuum potentially metastable [42–44].

After completion of the first two runs, the LHC has only gathered approximately 5% of its projected full dataset. During the second long shut down currently underway, the LHC is undergoing important upgrades in order to prepare for its high luminosity phase. The foreseen larger datasets to be collected during Run 3 and ultimately during the High Luminosity LHC (HL-LHC), will enable yet more fundamental and challenging measurements to explore new physics.

2.3 The Higgs Mechanism

In the SM [13–15], electroweak symmetry breaking [16, 17] is responsible for generating mass for the W and Z gauge bosons rendering the weak interactions short ranged. The SM scalar potential reads:

$$V(\phi) = m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \tag{2-2}$$

with the Higgs field ϕ being a self-interacting SU(2)$_L$ complex doublet (four real degrees of freedom) with weak hypercharge $Y = 1$ (the hypercharge is normalized such that $Q = T_{3L} + Y/2$, where Q is the electric charge and T_{3L} the eigenvalue of the diagonal generator of SU(2)$_L$):

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^{+} \\ \phi^{0} + i a^{0} \end{pmatrix}, \tag{2-3}$$

where ϕ^0 and a^0 are the CP-even and CP-odd neutral components, ϕ^+ is the complex charged component of the Higgs doublet, and $V(\phi)$ is the most general renormalizable scalar potential. If the quadratic term is negative, the neutral component of the scalar doublet acquires a non-zero vacuum expectation value (vev)

$$\langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \tag{2-4}$$

with $\phi^0 = H + \langle\phi^0\rangle$ and $\langle\phi^0\rangle \equiv v$, inducing the spontaneous breaking of the SM gauge symmetry SU(3)$_C$×SU(2)$_L$×U(1)$_Y$ into SU(3)$_C$×U(1)$_{\text{em}}$. The global minimum of the theory defines the ground state, and spontaneous symmetry breaking implies that there is a (global and/or local) symmetry of the system that is not respected by the ground state. From the four generators of the SU(2)$_L$×U(1)$_Y$ SM gauge group, three are spontaneously broken, implying that they lead to non-trivial transformations of the ground state and indicate the existence of three massless Goldstone bosons identified with three of the four Higgs field degrees of freedom. The Higgs field couples to the W_μ and B_μ gauge fields associated with the SU(2)$_L$×U(1)$_Y$ local symmetry through the covariant derivative appearing in the kinetic term of the Higgs Lagrangian,

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger (D^\mu\phi) V(\phi) \tag{2-5}$$

where $D_\mu\phi = (\partial + ig\sigma^a W^a_\mu/2 + ig'YB_\mu/2)\phi$, g and g' are the SU(2)$_L$ and U(1)$_Y$ gauge couplings, respectively, and σ^a, with a = 1,2,3, are the usual Pauli matrices. As a result, the neutral and the two charged massless Goldstone degrees of freedom mix with the gauge fields corresponding to the broken generators of SU(2)$_L$ and U(1)$_Y$ and become, in the unitary gauge, the longitudinal components of the Z and W physical gauge bosons, respectively. The Z and W

gauge bosons acquire masses,

$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{(g'^2 + g^2) v^2}{4} \tag{2-6}$$

The fourth generator remains unbroken since it is the one associated to the conserved $\mathrm{U}(1)_{\mathrm{em}}$ gauge symmetry, and its corresponding gauge field, the photon γ, remains massless. Similarly the eight color gauge bosons, the gluons, corresponding to the conserved $\mathrm{SU}(3)_C$ gauge symmetry with 8 unbroken generators, also remain massless (though confined inside hadrons and mesons as the result of the asymptotic freedom behaviour of QCD). Hence, from the initial four degrees of freedom of the Higgs field, two are absorbed by the $W^\pm$ gauge bosons, one by the Z gauge boson, and there is one remaining degree of freedom, H, that is the physical Higgs boson — a new scalar particle first imagined by P. Higgs [16, 17]. The Higgs boson is neutral under the electromagnetic interactions and transforms as a singlet under $\mathrm{SU}(3)_C$ and hence does not couple at tree level to the massless photons and gluons.

The fermions of the SM acquire mass through renormalisable interactions between the Higgs field and the fermions: the Yukawa interactions,

$$\mathcal{L}_{\mathrm{Yukawa}} = -\hat{h}_{d_{ij}} \bar{q}_{L_i} \phi d_{R_j} \hat{h}_{u_{ij}} \bar{q}_{L_i} \tilde{\phi} u_{R_j} \hat{h}_{l_{ij}} \bar{l}_{L_i} \phi e_{R_j} + h.c. \tag{2-7}$$

which respect the symmetries of the SM but generate fermion masses once EWSB occurs. In the Lagrangian above, $\tilde{\phi} = i\sigma_2 \phi^*$ and q_L (l_L) and u_R, d_R (e_R) are the quark (lepton) $\mathrm{SU}(2)_L$ doublets and singlets, respectively, while in each term $\hat{h}_{X_{ij}}$ is parametrized by a 3×3 matrix. The mass term for neutrinos is omitted, but could be added in an analogous manner to the up-type quarks when right-handed neutrinos are supplementing the SM particle content (neutrinos can also acquire Majorana masses via non-renormalizable dimension-5 interactions with the Higgs field [45]). Once the Higgs field acquires a vev, and after rotation to the fermion mass eigenstate basis that also diagonalizes the Higgs-fermion interactions, $\hat{h}_{f_{ij}} \to h_{f_i} \delta_{ij}$, all fermions acquire a mass given by $m_{f_i} = h_{f_i} v / \sqrt{2}$. The indices $i,j = 1,2,3$ refer to the three families in the up quark, down quark or charged lepton sectors. It should be noted that the EWSB mechanism provides no additional insight into possible underlying reasons for the large variety of masses of the fermions, often referred to as the flavor hierarchy. The fermion masses, accounting for a large number of the free parameters of the SM, are simply translated into Yukawa couplings.

2.4 Shortcomings of the SM

The SM has only mathematically accommodated the strong, EM, and weak forces. One problem however is that the SM can't predict the mass of the Higgs boson... or the mass of *any* particle for that matter. That's not the only thing the SM has trouble doing. For example, the SM can't...

- ...incorporate gravity into its mathematical framework.
- ...explain why most of the Universe is made of matter and very little antimatter.
- ...predict the existence of dark matter - but we know it's there from observation.
- ...explain why there should be exactly three generations of fermions.

No Gravity. Can't combine quantum mechanics and gravity. No neutrino masses. Are they Direac or Majorana particles? Higgs field parameters appear highly fine-tuned. Does not explain dark matter or dark energy.

So we see that the SM isn't the ultimate Theory of Everything, but it does a pretty good job. How can we test the SM and try to break it or confirm it? There are at least two routes to choose from: A patient route and an impatient route. The patient route requires us to wait until our particles of interest maybe come from outer space or, if we produce it in the lab, wait for it to decay into other particles. This could take a VERY long time, (possibly way longer than the age of the Universe - if a proton even decays at all!), or it could take as short as a billionth of a billionth of a millionth of a second, like in the case of a Z boson. It's not the most reliable method, it is difficult to control, and it requires a lot of patience. - Origin of mass: yes, the Higgs boson—but is it certainly the same Higgs boson as predicted by the SM? - SUSY: - A way to unify the fundamental forces (all 4?) but SM doesn't predict SUSY particles. - Do they exist? No evidence yet.

- Dark matter/Dark Energy: - Rotational velocity data from the outer reaches of our own galaxy suggest that there is much more matter in the universe that what has been directly observed. The SM has no explanation for dark matter dark energy.

- Matter/Antimatter Asymmetry: - The Big Bang supposedly (TODO) produced equal amounts of matter and antimatter. - So why is the universe made of *only* matter?

Instead, let's be impatient: let's smash particles together and convert their energies into new kinds of matter. If we use hadrons, which are made of smaller parts like, quarks and gluons (let's call them "partons") then we will have many more interactions and a lot more fun (Fig. **??**). We are going to need a lot of energy, so we should make a large collider. Let's make a Large Hadron Collider!

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BIOGRAPHICAL SKETCH

Jake Rosenzweig had the best childhood anyone could ask for, growing up in Jacksonville, FL: enjoying video games with excellent friends, playing football on the beach, and having plenty of opportunity to make mistakes. He graduated from the University of Florida in 2011 with a B.S. in chemistry, while maintaining his sanity by getting minors in education and Latin. He enjoys building things from scrap, weightlifting, hiking in the Coloradoan mountains, gardening, silence, and—most of all—receiving the beleaguered stare from his wife after telling her a *particularly* bad dad joke.